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ABSTRACT

Hybrid ground source heat pump (HyGSHP) systems are gaining popularity as a means of decreasing long term energy and maintenance costs while maintaining manageable first costs. The incorporation of a supplemental heat rejecter into a standard GSHP design introduces several complexities. One of the major challenges involves determining the optimal control strategy for such a system. This paper includes a review of HyGSHP control strategies followed by a more detailed discussion of the pre-cooling strategy. This strategy incorporates thermal storage into the system in order to shift power consumption to periods with off-peak electric rates, thereby reducing operating costs. The results of a preliminary study of pre-cooling as well as plans for further research will be presented.

1. INTRODUCTION

An air source heat pump is an efficient method to meet both heating and cooling loads, but its performance is limited by the fact that the outdoor air is the heat source or sink. On a hot summer day heat is rejected from the building to the hot outdoor air, leading to a reduction in heat pump efficiency. Below the frost line the ground temperature is nearly constant year round, making it a much better heat source or sink. On a hot summer day heat is rejected not to the hot outdoor air, but to the much cooler ground. A ground source heat pump (GSHP) is, therefore, a reliable method to improve heat pump performance. A typical GSHP design contains a number of boreholes drilled to a depth on the order of 100 m; polyethylene pipe is placed in the boreholes, which are backfilled with a thermally conductive grout. As fluid flows through the bore-field energy is removed from the ground for heating or rejected to the ground for cooling. Ideally the cooling and heating loads are balanced, so over time the temperature of the ground is relatively unchanged. However, large commercial buildings are typically cooling dominated; cooling loads are larger than heating loads. In addition, when the building loads are large, as is typical in commercial buildings, many boreholes are required, leading to a significant first cost.

A Hybrid GSHP (HyGSHP) can mitigate the load imbalance and reduce the number of boreholes in the system, thereby reducing first cost. For example, in a cooling dominated building a cooling tower (CT) can be added to the GSHP as a supplemental heat rejecter. A study conducted by the Energy Center of Wisconsin (Energy Center of Wisconsin 2011; Hackel & Pertzborn 2011) compared the energy and water costs of a conventional system, a GSHP system, and a HyGSHP system in three different buildings. The GSHP and HyGSHP systems had lower energy and water costs as compared to the conventional system. Although the cost of operating the HyGSHP system was slightly greater than operating the GSHP, it was still substantially less than the conventional system and the first cost was lower than the GSHP system. This study demonstrated the potential of HyGSHP systems.

One of the key design decisions in a CT HyGSHP is how to control each component in the system. The current work contains a discussion of potential control strategies followed by a more in depth discussion of the pre-cooling strategy.

2. CT HyGSHP CONTROL STRATEGIES

Several prior studies have examined control strategies for CT HyGSHP systems. Three strategies are set point temperature control (T_{set}), differential temperature control (T_{diff}), and pre-cooling (PC). For the T_{set} strategy the CT operates when the fluid temperature exceeds a specified set point temperature. For the T_{diff} strategy the CT operates when the fluid temperature exceeds the wet bulb temperature by a specified set point, ensuring that the CT does not operate if the environmental and fluid conditions are unfavorable for efficient and effective operation. Pre-cooling (PC) is designed to use the ground as a thermal storage device. The CT is used to cool the ground, which can then be used to cool the building at a later time more efficiently than if it were not pre-cooled. PC is an indirect method of meeting the building load by increasing the cooling capacity of the ground. These strategies can also be used in combination. This section reviews some of the research into HyGSHP control strategies.

Yavuzturk and Spitler (Yavuzturk & Spitler 2000) studied all three of these strategies, implementing them in a variety of ways. They evaluated the T_{set} strategy with the fluid temperature measured at either the inlet or outlet of the heat pump. The T_{diff} strategy was evaluated using the difference between the fluid temperature entering or exiting the heat pump and the wet bulb temperature; one differential temperature set point turned the CT on and another turned it off. The set point temperature (T_{set}) and differential temperature (T_{diff}) were constant values selected by the authors. PC was evaluated by activating it in three different ways; the CT operated between 0:00 and 6:00 all year, between 0:00 and 6:00 from January through March, or between 0:00 and 6:00 from June through August. The second implementation is an example of seasonal PC while the last implementation is an example of diurnal PC; both are described in the next section. PC was combined with T_{set} in all three cases. The size of the GHX and CT were not optimized, nor was the implementation of any of the strategies optimized. The authors compared the performance of the hybrid system to a baseline GSHP system in Houston, TX and Tulsa, OK. In all cases the addition of a CT led to a reduction in power consumption, but the cases using T_{diff} control produced the greatest reduction. The authors also performed an economic analysis of each system; the analysis did not include the cost of water or time of day electrical rates. The analysis indicates that all of the hybrid designs save money, with the T_{diff} strategy having the greatest cost reduction. Yi, et al. (Yi et al. 2008) simulated a CT HyGSHP system in Hong Kong, using T_{set}, T_{diff}, and PC with T_{set} for a 10 year simulation period. This study also showed that T_{diff} produces the greatest decrease in operating costs and power consumption. The items included in the operating cost calculation are not individually presented and the cost of the water used in the CT may not be included.

Fan, et al. (Fan et al. 2008) analyzed a less traditional CT HyGSHP system. Their goal was to design a system and control strategy that would shift power consumption from periods of peak electrical rates to periods of off-peak electrical rates (peak/off-peak = 3); the success of the system was based primarily on the success of this shift. The CT was used as a direct means of meeting cooling loads, but it was not used for PC. Instead, the heat pumps were used to cool the ground at specific times of the year. During these PC periods the heat pumps produce -5°C fluid which is used to cool the ground. In some cases this resulted in fluid that was cold enough to be used directly for cooling, bypassing the heat pump. Nearly 73% of the energy removed from the ground at night was replaced during the day in order to meet the cooling load; 27% of the cooling potential created by PC was lost. They also found that the power consumption was reduced during periods with cooling loads. This analysis did not include all sources of power consumption (most significantly the circulating pump power) and did not include a cost analysis.

These studies provide a foundation for the study of the operation of HyGSHP systems, but the economic analyses are limited and the component sizes and control set points are not optimized. The T_{diff} strategy appears to be the most promising, so the goal of this work is to more fully evaluate PC in order to determine if it should be considered for further study.

3. PRE-COOLING

There are two general forms of pre-cooling, diurnal and seasonal. In seasonal PC the ground is cooled during a time of the year when there are low or no cooling loads; for example, the CT could be used to cool the ground during the spring in order to improve cooling efficiency during the coming summer. In diurnal or short term PC, the ground is cooled during the night at times of the year when cooling loads are high in order to improve the cooling efficiency the following day. Diurnal PC is the focus of the current work, though some of the findings will inform additional work on seasonal PC.

The current work focuses on developing a fundamental understanding of PC and determining how best to implement it in a HyGSHP system.

3.1 Thermal Storage Efficiency of the Ground

A numerical model of a hollow cylinder was used to determine the feasibility of using the ground as a thermal store. This was a simple one-dimensional conduction model with a constant temperature outer boundary and a time varying constant temperature inner boundary. When heat is rejected to the ground, as when there is a cooling load, the inner boundary is 3°C above the undisturbed ground temperature; when heat is removed, as in PC, the inner boundary is 3°C below the undisturbed ground temperature. If there is no heat transfer, the inner boundary is adiabatic.

The purpose of this analysis was to determine the theoretical maximum additional energy that could be rejected to the ground given a removal of energy during the night via PC. First, a baseline case without PC was simulated to determine how much energy could be rejected into the control volume during a 200 day time period; 200 days was chosen to ensure that a steady state was reached. Three PC cases were compared to this baseline case. In Case A heat was removed from the ground for a 12 hour PC period and then rejected to the ground for the remaining 200 day period. In Case B the PC period was 6 hours long, followed by a 6 hour period with an adiabatic boundary condition, and then followed by a 200 day period of heat rejection. In Case C there was a 6 hour period with an adiabatic boundary condition followed by a 6 hour PC period and then a 200 day heat rejection period. This model is intended to simulate an infinitely long day after PC in order to determine the maximum thermal storage efficiency, η_s, defined in Equation (1).

$$\eta_s = \frac{q_{in,pc} - q_{in}}{q_{out}} \bullet 100 \tag{1}$$

$q_{in,pc}$ is the heat rejection to the ground when PC has been used to remove heat, q_{in} is the heat rejection when PC is not used, and q_{out} is the heat removed by PC. The storage efficiency for each case is shown in Table 1.

Table 1: Thermal storage efficiency.

Case	Storage Efficiency
A	68%
B	69%
C	73%

Approximately 30% of the energy removed in PC is not replaced during the day; this is lost cooling potential and it is very similar to the loss estimated by Fan et al. PC is not the most effective way of meeting a load which occurs at a later time because of these losses. However, PC may be cost effective by shifting some of the energy consumption to periods when off-peak electrical rates apply and, by reducing the temperature of the fluid entering the heat pump, the efficiency of the heat pump can increase. These effects are evaluated by constructing a more complete system model.

3.2 System Model

The layout of the system model is shown in Figure 1, where HP is the heat pump, GHX is the ground heat exchanger, and CT is the cooling tower. The HP is a single large heat pump which simulates the effect of a large number of heat pumps; more information about this model can be found in the references (Hackel 2008; Xu 2007). The heat pump performance is based on manufacturer data. The HP operates whenever there is a building load and the flow rate through the HP is based on the magnitude of that load. The bypass around the HP is used if the flow rate through the heat pump is less than 30% of the maximum system flow; this ensures that the circulating pumps (not shown) operate above a minimum speed. The fluid then passes through the GHX where heat is rejected to the ground. In PC operation, fluid leaves the CT and enters the GHX, cooling the ground.

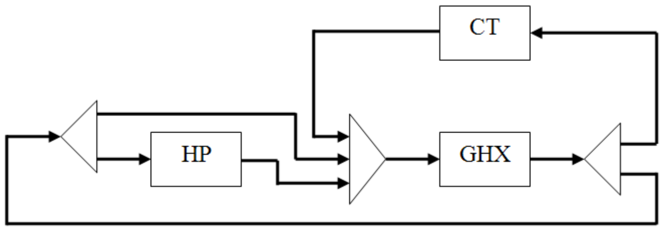

Figure 1: Schematic of the system model.

3.3 Single Day Load

In order to meet the needs of this initial investigation of PC, a synthetic building cooling load was developed such that the peak load occurs in the afternoon and the load occurs only between 8:00 and 20:00. PC is used during the hours when there is no load, so there is never a time when the CT and HP are both in operation. This cooling load is repeated for every day of a 20 year simulation in two locations, Las Vegas, NV and Chicago, IL.

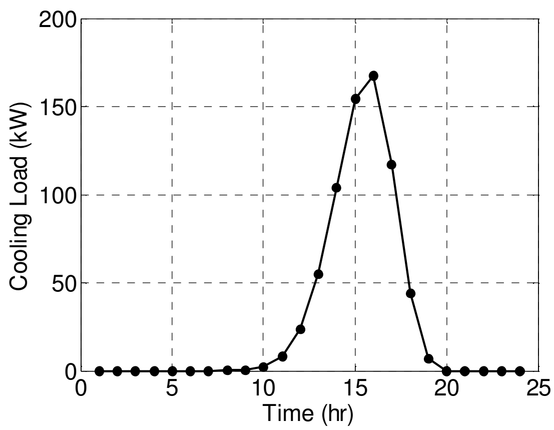

Figure 2: Cooling load profile.

The P1-P2 method (Duffie & Beckman 2006) for Life Cycle Cost (LCC) calculation was used to evaluate the cost effectiveness of PC. The key economic parameters (applied to the analysis in both locations) are given in Table 2; time of day rates and the cost of water are considered in this analysis.

Table 2: Key Economic Parameters.

Effective income tax rate	35%
Property tax rate	3%
Duration of the economic analysis	20 years
Fuel inflation rate	1.33%
Discount rate	8.5%
Down payment	100%
Minimum time frame in the analysis	20 years
Depreciation life	5 years
First cost of GHX	39 $/m
Cost of water	1.41 $\$/m^3$
Peak rate (11:00 to 20:00)	0.104 $/kWh
Off-peak rate	0.057 $/kWh

Two cases were considered: 1) no PC and 2) PC was added. In both cases the size of the CT and GHX were optimized using the subplex optimization scheme described in the references (Rowan 1990) in order to minimize LCC while maintaining the temperature of the fluid entering the HP between 1.7°C and 35°C. In Las Vegas the optimal GHX length without PC is 10,700 m; if PC is used every night, the optimal GHX length is 2854 m and the CT size is 157 kW. The performance of the optimized PC case is compared to that of the baseline case in Table 3. The addition of a CT helps balance the ground load, resulting in lower ground temperatures, more efficient heat rejection during the day, and a decrease in HP power consumption. The CT mitigates the increase in ground temperature that occurs under normal conditions, therefore the GHX can be substantially smaller, saving a significant amount of up front cost. Despite the decrease in HP power consumption, the overall operational cost and power consumption increase due to CT operation as well as the operation of the circulating pump. The cost of water is also a significant factor.

Table 3: Economic and power results as compared to the baseline case in Las Vegas, NV.

	First cost ($)	Electrical cost ($)	Water cost ($)	LCC ($)	HP Power (kWh)	Additional Power (kWh)
PC case	-293,252	11,663	12,892	-250,945	-11,453	332,896

The results are similar for the simulation in Chicago, as shown in Table 4. Without PC the optimal GHX length is 4650 m; with PC the optimal length is 2910 m and the CT size is 166 kW. One interesting observation from Chicago is that PC is not effective in the first several years of operation. The undisturbed ground temperature in Chicago is approximately 13°C while the wet bulb temperature is between 17°C and 25°C. Since the wet bulb temperature is greater than the ground temperature, the CT heats the ground. As the simulation progressed, more heat was rejected to the ground and the ground temperature became greater than the wet bulb temperature, so after the first several years the CT began to cool the ground. However, when the CT heated the ground the HP power consumption increased more than it decreased during the later years, so the overall result was an increase in HP power consumption. This effect illustrates the importance of implementing PC in an intelligent manner so that it always operates as expected.

Table 4: Economic and power results as compared to the baseline case in Chicago, IL.

	First cost ($)	Electrical cost ($)	Water cost ($)	LCC ($)	HP Power (kWh)	Additional Power (kWh)
PC case	-54,612	16,761	4053	-29,652	75,522	359,326

3.6 Annual Load

The repeated single cooling day load is not realistic, so a more typical annual load was used for a 20 year simulation in Las Vegas; see Figure 3. The heating loads were removed from the load profile because these loads could be met by a boiler rather than the ground. As in the single day simulation PC was used every night for 12 hours, but unlike that case there were times when cooling loads were present during the PC period. In a more optimal system PC might not be used every night of the year. The optimal GHX length without PC is 106,650 m; with PC the optimal length is 29,223 m and the CT size is 2243 kW.

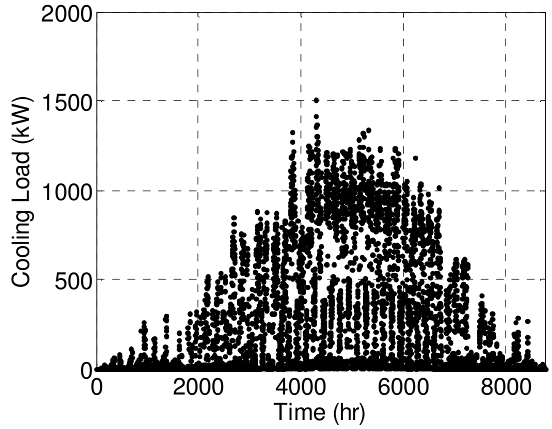

Figure 3: Annual cooling load.

The results are shown in Table 5. The trend is the same as for the single day load case. There is a significant decrease in the first cost of the system because the CT balances the ground load, allowing for a smaller GHX, but there is an increase in power consumption and electrical and water cost due to the CT and circulating pump operation.

Table 5: Economic and power results as compared to the baseline case in Las Vegas, NV, with annual loads.

	First cost ($)	Electrical cost ($)	Water cost ($)	LCC ($)	HP Power (kWh)	Additional Power (kWh)
PC case	$-2.93*10^6$	112,159	78,673	$-2.58*10^6$	-789,886	4,034,972

4. DISCUSSION

The numerical model showed that the thermal storage efficiency of the ground is approximately 70%; this means that by meeting some of the load through indirect operation of the CT (e.g. the CT cools the ground, not the building), 30% of the cooling potential is lost. However, the efficiency is sufficiently high that this loss could be offset by the improvement in the heat pump performance and there is also a potential economic benefit by operating during off-peak periods. The single day model used a system composed of a CT, HP, and GHX in order to assess the power consumption and economic benefit of adding PC to a GSHP system. As expected, PC led to a reduction in HP power consumption, but this reduction was offset by an overall increase in power consumption due to the addition of the CT and the cost of operating the circulating pump during PC. However, the addition of the CT led to a more balanced ground load, which led to a smaller GHX and a significant reduction in first cost. The annual load simulation showed similar results. These studies indicate that the benefit of PC is not in a reduction in operating cost, but in the reduction of the GHX length and therefore first cost. This means that in general a HyGSHP is more cost effective than a GSHP, but it does not mean that PC is the best control strategy for such a system.

5. CONCLUSIONS

This paper details a limited study of the PC strategy. The addition of a CT led to a more balanced ground load and a decrease in the size of the GHX. This saves a significant amount of the first cost of the system. This study has effectively shown that a CT hybrid ground source heat pump can be very cost effective, but the optimal control strategy has yet to be determined. Although PC was effective, it is likely that using the T_{diff} or T_{set} control strategies will be more effective because the CT can be used to meet the load directly without the loss in cooling potential. In this study, the difference between the peak and off-peak electric rates was not large enough to lead to a significant cost reduction by operating the CT at night. The cost of water can also be significant, so any savings gained by operating during off-peak periods has to offset this substantial cost increase.

The next step in this research is to create a system model which uses a control strategy such as T_{diff} in order to meet the cooling load directly with the CT. PC can then be added to this system to determine if it is effective in combination with another strategy. The PC operation will take into account some of the lessons from the current work. For example, in Chicago PC is detrimental for cooling until the ground temperature has increased, so a PC strategy would need to take this into account. A sensitivity study will also be performed to assess how much greater the peak cost must be as compared to the off-peak cost in order to make PC beneficial. A further step is to evaluate the PC strategy with a more ideal thermal storage device, such as a thermal storage tank.

NOMENCLATURE

CT	cooling tower	
η	efficiency	
GHX	ground heat exchanger	
GSHP	ground source heat pump	
HP	heat pump	
HyGSHP	hybrid ground source heat pump	
LCC	life cycle cost	($)
PC	pre-cooling	
q	heat transfer	(kW/m)
T	temperature	(°C)

Subscripts

diff	differential
in	in
out	out
s	storage
set	set point

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